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# Multichannel nonlinear distortion compensation using optical phase conjugation in a silicon nanowire

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**Abstract:** We experimentally demonstrate compensation of nonlinear distortion caused by the Kerr effect in a  $3 \times 32$ -Gbaud quadrature phase-shift keying (QPSK) wavelength-division multiplexing (WDM) transmission system. We use optical phase conjugation (OPC) produced by four-wave mixing (FWM) in a 7-mm long silicon nanowire. A clear improvement in Q-factor is shown after 800-km transmission with high span input power when comparing the system with and without the optical phase conjugation module. The influence of OSNR degradation introduced by the silicon nanowire is analysed by comparing transmission systems of three different lengths. This is the first demonstration of nonlinear compensation using a silicon nanowire.

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## 1. Introduction

Coherent systems are becoming increasingly used in optical communications since they enable compensation of dispersive transmission impairments in the digital domain and make it possible to use advanced modulation formats such as quadrature phase shift keying (QPSK) and quadrature amplitude modulation (QAM) to increase the spectral efficiency and provide enhanced capacity. However, these multi-level modulation formats require higher optical signal-to-noise ratios (OSNRs) to maintain sufficient bit-error-ratios after transmission. In order to ensure higher OSNR values in fiber transmission systems without changing the optical amplification configuration, the launched power into each fiber span needs to be increased, which in turns excite nonlinearities that distort the signal and decrease the performance of the system [1]. This is even more pronounced in wavelength division multiplexing (WDM) systems where nonlinear crosstalk between the channels results in significant degradation of the signal quality. Consequently, mitigation of nonlinear effects is needed. Digital backpropagation (DBP) appears as a possible candidate for solving this issue [2]. However, DBP adds complexity at the receiver, increases the power consumption of the system and can increase the latency of transmission. Therefore, some approaches based on all-optical signal processing [3–6] have recently regained interest in the context of nonlinear distortion compensation. In particular nonlinear distortion compensation based on optical phase conjugation (OPC) [7] has led to a number of demonstrations in systems carrying Tb/s data signals [8–10].

Even though highly nonlinear fibers (HNLFs) stand as the most promising platform for all-optical signal processing so far, thanks to their reduced propagation and coupling losses, they however suffer from some limitations, especially due to stimulated Brillouin scattering (SBS) and limited dispersion engineering. Additionally, due to their long interaction lengths, HNLFs are not good candidates for integrated solutions, even though some compact implementations have been demonstrated [11]. At the device level, there has been some

demonstrations of nonlinear distortion compensation in periodically polled LiNbO<sub>3</sub> waveguides [12–14]. However, these waveguides are typically several cm long, resulting in large footprints for the nonlinear processing elements. Furthermore, wavelength conversion in standard PPLN waveguides is not continuously tunable in practice since it relies on quasi-phase matching of the second-harmonic generation (SHG) process. Although the quasi-phase matching wavelength range can be broadened [15], this comes at the expense of reduced conversion efficiency. Over the past decade, much progress has been made in the development of silicon-based integrated photonic devices. Silicon has a high nonlinear refractive index, is transparent in the telecommunications wavelength range and, more importantly, is compatible with complementary metal-oxide-semiconductor (CMOS) fabrication technology. Nano-engineered waveguides fabricated on the silicon-on-insulator (SOI) platform, so-called nanowires, have been intensively investigated as key components for nonlinear silicon photonics. These nanowires may not exhibit SBS, offer the possibility for widely tunable dispersion engineering enabling large conversion bandwidths and, due to strong confinement, show large nonlinear coefficients. These properties make them very attractive for all-optical signal processing. Ultra-high speed [16] and complex modulation format [17] signals have been successfully processed using silicon nanowires, highlighting their great potential. Furthermore, the use of silicon nanowires as an optical phase conjugator has been demonstrated [18]. The drawback of silicon waveguides is the presence of two-photon absorption (TPA) induced free-carrier absorption (FCA) that causes nonlinear loss limiting the total power that can be launched into the waveguide, hence the efficiency of the parametric processes. However, this issue can be solved by implementing reverse-biased p-i-n diode structures across the waveguides, leading to high conversion efficiencies, and values as high as –1 dB have so far been demonstrated [19].

In this paper, all-optical compensation of the distortion induced by nonlinear effects in a  $3 \times 32$ -Gbaud QPSK WDM coherent transmission system is demonstrated using a silicon nanowire as optical phase conjugator placed in the middle of the transmission link. The performance of 480-km, 640-km and 800-km long dispersion unmanaged transmission links has been characterized and compared. When 13 dBm of signal power is launched into each transmission span of the 800-km link, the performance of the system without OPC is below the standard forward-error-correction (FEC) limit (corresponding to a Q-factor of 9.8 dB), while when OPC is introduced in the system, the measured Q-factor is significantly enhanced, reaching values as high as 13.3 dB.

## 2. System description

Figure 1(a) shows the experimental setup of the transmission system, which uses a silicon nanowire as an optical phase conjugator. The system comprises a WDM QPSK transmitter, a dispersion-unmanaged optical transmission link, an OPC module placed in the middle of the link, and a coherent receiver. The optical transmission link was built from 80-km standard single mode fiber (SSMF) spans having a total loss of around 16 dB and erbium-doped fiber amplifiers (EDFAs). The total power launched into each span was set by varying the output powers of the EDFAs within their tuning ranges (8 dBm to 13 dBm).

The transmitter, represented in Fig. 1(b), consisted of three continuous-wave (CW) distributed feedback (DFB) lasers with 100-GHz channel spacing at 1548.3 nm, 1549.1 nm and 1549.9 nm. The three waves were coupled together and modulated using an in-phase/quadrature (IQ) modulator driven by two pseudo-random binary sequences (PRBSs) of lengths  $2^{20}-1$  and  $2^{15}-1$  generated from a bit-pattern generator (BPG) working at 32 Gbps, resulting in  $3 \times 32$ -Gbaud QPSK data signals. After being transmitted over the first half of the transmission link, the signal was input either to the OPC module, as shown in Fig. 1(c), or directly to the next transmission span, bypassing the OPC module. Nonlinear compensation based on OPC relies on the fact that the regions of the link where the signal power is high should be symmetrically distributed when plotted on a power versus accumulated dispersion diagram [4]. In order to increase the symmetry of the system with respect to the OPC operation and therefore improve the nonlinear distortion compensation, the signal was

propagated through a piece of dispersion-compensating fiber (DCF) before being phase conjugated in the nonlinear silicon waveguide. The DCF used in our experiment had a total dispersion of  $-1026$  ps/nm and 5 dB of insertion loss. An important advantage of this scheme is that the transmission link does not need in-line dispersion compensators. At the OPC module input, the WDM signal was amplified in an EDFA and filtered by a 3-nm optical band-pass filter (OBPF) to suppress out-of-band amplified spontaneous emission (ASE) noise. The pump was generated from an external cavity laser (ECL) at 1552.8 nm, amplified by an EDFA, filtered by a 1-nm OBPF and combined with the WDM signal in a 3-dB coupler. The pump and signal were then coupled into the silicon nanowire via tapered fibers.

The silicon nanowire used in the experiment was 7-mm long with a  $220\text{ nm} \times 460\text{ nm}$  cross-section and it was tapered down to 200 nm in width in order to decrease coupling loss to tapered fibers. The waveguide was fabricated on an SOI substrate with a  $2\text{-}\mu\text{m}$  thick buried oxide and covered with  $2\text{-}\mu\text{m}$   $\text{SiO}_2$  as the upper cladding. Coupling loss and propagation loss for the TE mode were estimated to be 4 dB/facet and 3 dB/cm, respectively, leading to around 10.8 dB of total insertion loss. The polarizations of the pump and signal at the input of the Si nanowire were controlled by polarization controllers, as shown in Fig. 1(c) and aligned to the TE mode of the waveguide in order to maximize the FWM conversion efficiency. A limitation of this scheme is that it is polarization sensitive and therefore is not suitable for polarization-multiplexed signals and is susceptible to fluctuations of the signal state of polarization over the first half of the link. In order to make the scheme polarization insensitive, a polarization diversity scheme such as the one we recently demonstrated in [20] can be used. The wavelength-converted and phase-conjugated signals at the output of the silicon nanowire were filtered with two OBPFs before transmission over the second half of the link.

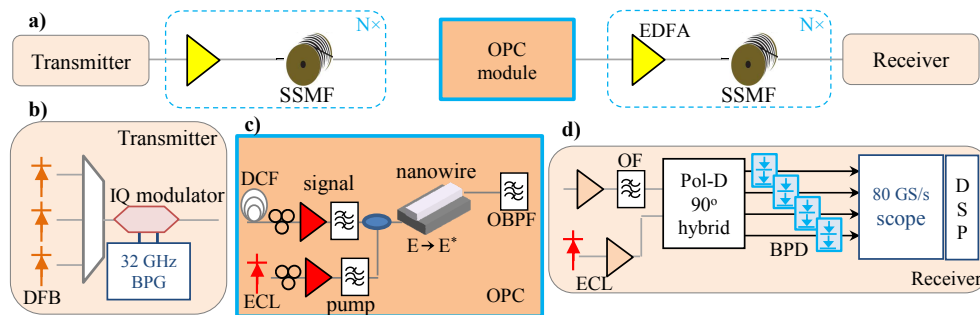


Fig. 1. Experimental setup. (a) Dispersion-unmanaged transmission system with OPC module. (b) WDM QPSK transmitter. (c) OPC module. (d) Coherent receiver.

After transmission, the signal was input to a polarization-diversity coherent receiver for detection and Q-factor measurements. The coherent receiver consisted of an optical 90-degree hybrid circuit, four balanced photodetectors (PDs) and a tunable ECL as local oscillator (LO), as shown in Fig. 1(d). The outputs of the PDs were then input to a 4-channel real-time oscilloscope (Agilent DSOX96204Q) with 80-Gsamples/s sampling rate and 32-GHz electrical bandwidth. The captured data were processed offline through standard steps of digital signal processing (DSP), which included data resampling, residual dispersion compensation, time-domain equalization (constant modulus algorithm) and phase recovery (Viterbi-Viterbi algorithm). In the system without OPC, the chromatic dispersion accumulated along the link was compensated using DSP in the receiver. The OPC provides automatic second order chromatic dispersion compensation after signal transmission over the link and therefore only the dispersion caused by the DCF was compensated using DSP. The performance was characterized by evaluating the Q-factor from the Cartesian spreads of the constellations, as presented in [21], over 200 000 collected symbols.

### 3. Experimental results

The total signal power at the input of the silicon nanowire was 16 dBm while the pump power was 22.4 dBm, resulting in  $-25.5$  dB of conversion efficiency (CE, defined as the ratio between the idler power and signal power at the output of the nanowire), as shown in the output spectrum presented in Fig. 2(a). For 23.4 dBm of total input power, the insertion loss of the waveguide was increased by 3.2 dB compared to the low power case, due to nonlinear loss. Slightly different conversion efficiencies were measured for the different WDM channels, possibly due to different states of polarization after propagation over the first half of the link as a result of polarization mode dispersion (PMD).

The performance of the transmission system was characterized by measuring the Q-factor of the received signals as a function of the total power launched into each SSMF span. It should be noted that the OSNR was not artificially reduced in front of the receiver for all measurements. The performance measured for the 800-km long transmission link is compared for the systems with and without the OPC module in Fig. 2(b). At the lowest launched power the performance of the two systems is very similar. Here it can be noticed that the best performance is obtained for the middle channel, which is the one having the best OSNR after the OPC (the highest CE), hence at the receiver. This shows that, for the lower values of the investigated launched power range, the system with OPC is dominated by ASE noise rather than nonlinearities. In the strong nonlinear regime, the system with the OPC module in the middle of the link allows higher launched powers with a significant improvement in Q-factor compared to when no OPC is used. For 13 dBm launched power, the system without OPC shows a Q-factor slightly below the FEC limit of 9.8 dB, corresponding to a bit-error-ratio (BER) of  $10^{-3}$ . For the same launched power, the system with the OPC module shows 3.6 dB of improvement in Q-factor, confirming the effectiveness of the silicon waveguide as an optical phase conjugator for nonlinear distortion mitigation in a transmission link. This improvement is clearly seen in Fig. 2(c), where the constellation diagrams of all three WDM channels are represented when 13 dBm of power was launched into each span. Nonlinear distortion is obvious in the constellation diagrams for the system without the OPC module, while the distortion is compensated when the OPC module is present in the system. By improving the Q-factor of the received signal for high launched powers, the total transmission distance could be increased without increasing the number of EDFAs in a system by having longer spans of SSMF [21].

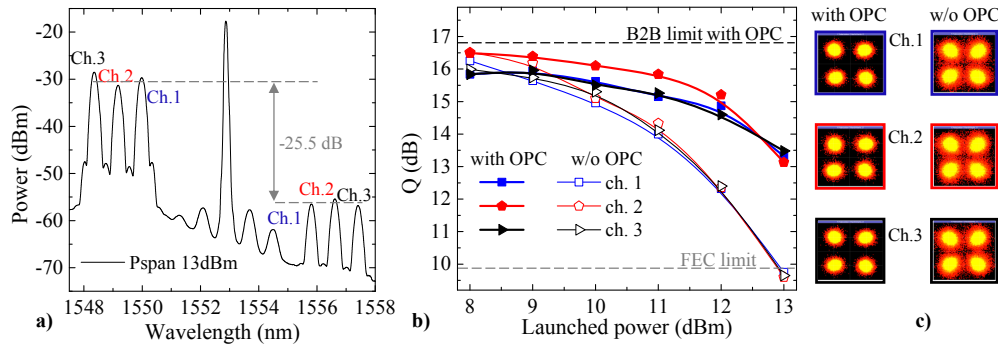


Fig. 2. Performance for the 800-km link. (a) Spectrum at the output of the silicon nanowire. (b) Q-factor versus power launched into each span. (c) Constellation diagrams for all three channels with and without the OPC module for 13 dBm launched into each span.

In order to further investigate the role of the OPC module in the system performance, the performance of links with three different transmission lengths (480 km, 640 km and 800 km) was compared. The evolutions of Q-factors averaged over all three WDM channels as a function of launched power are shown in Fig. 3(a), together with the corresponding averaged OSNRs in Fig. 3(b). The results can be compared to the best Q-factor for the system without

transmission but with OPC (referred to as back-to-back (B2B) limit with OPC), which was measured to be 16.9 dB, as indicated in Fig. 3(a) by the dashed line. This Q-factor was obtained for around 22 dB of OSNR, (indicated in Fig. 3(b)), which is the best OSNR value that could be obtained at the receiver. It should be noted that this Q-factor value is lower than the Q-factor obtained for a B2B signal without OPC, and the degradation is mainly coming from the relatively low CE, which could be improved by implementing a p-i-n diode for removal of the generated free carriers [19]. For the minimum launched power of 8 dBm, the performance of the transmission system with OPC is the same for all three transmission distances. It can also be observed from Fig. 3(a) that the system without OPC is already limited by transmission nonlinearities when the total launched power is 8 dBm (the roll-over expected when the signal degradation becomes dominated by noise is not visible in the investigated power range). Nevertheless the performance of the system without OPC is equivalent to, or even better, depending on the reach, than that of the system with OPC at this launched power. This suggests that the system with OPC is strongly affected by the OSNR degradation due to the low conversion efficiency of the OPC itself. For the highest launched power of 13 dBm, the Q-factor of the system with OPC is different for the three different transmission lengths, but the improvement compared to the system without OPC remains almost the same, i.e. around 3.6 dB, for all three transmission lengths, regardless of the fact that the OSNR of the signal in the system without OPC is 12 dB higher. This clearly demonstrates the benefit of nonlinearity compensation thanks to the OPC, even though the system with OPC is still ultimately limited by nonlinearities at such a high launched power level.

The use of DSP at the receiver enables to overcome the limitation due to the fact that all channels do not experience the same amount of dispersion before and after the OPC, as a consequence of the dispersion slope of the transmission fiber. Here, the residual dispersion can easily be compensated by the equalization stage in the DSP. Therefore the bandwidth of our system is essentially limited by the conversion bandwidth of the OPC itself. Based on its calculated dispersion properties, the 3-dB conversion bandwidth of the silicon waveguide used in our work is estimated to be of the order of 7 nm, meaning that only 5 WDM channel with 100-GHz spacing could be processed. However, this bandwidth can easily be enhanced by proper dispersion engineering of the waveguide.

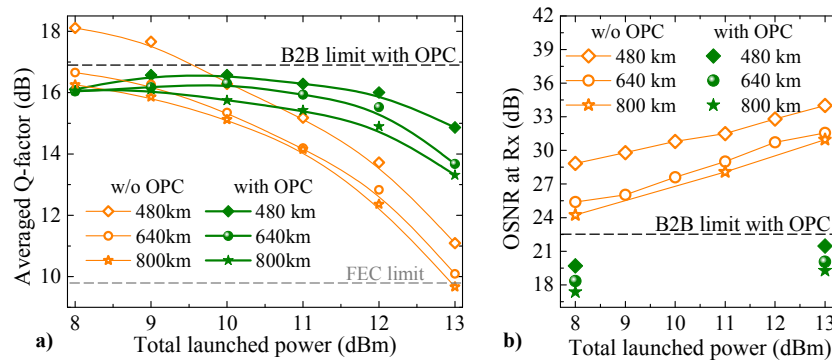


Fig. 3. (a) Q-factor averaged over the three channels and (b) OSNR at the receiver (Rx) versus power launched into each span for transmission with and without OPC over 480-km, 640-km and 800 km long links.

In order to quantify the requirements on the phase conjugator and its conversion efficiency, the system was characterized for a 480-km long link by measuring the improvement in Q-factor between the links with and without OPC for 13 dBm launched power, while changing the pump power into the nanowire and therefore the conversion efficiency of the signal in the OPC. The dependence of the conversion efficiency on the pump power is shown in Fig. 4(a). The measured Q-factor improvement is represented as a function of the CE in Fig. 4(b), together with the corresponding averaged OSNRs. Even though the



improvement in Q-factor is larger than 2 dB, even for conversion efficiencies lower than  $-30$  dB, it is clear that higher conversion efficiencies result in larger improvements in Q-factor due to the higher OSNR at the receiver.

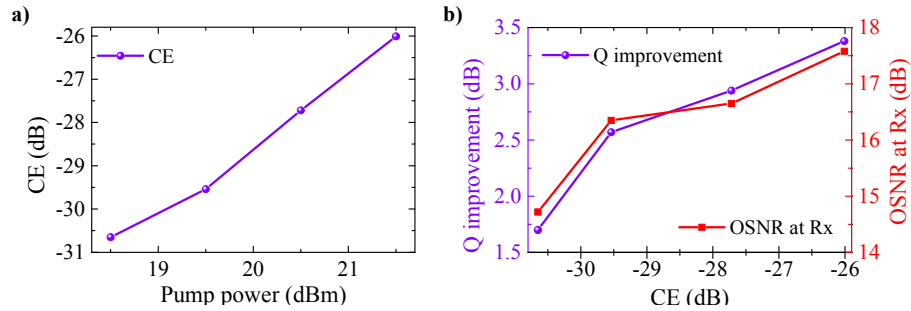


Fig. 4. a) FWM conversion efficiency as a function of pump power launched into the waveguide. b) Improvement in averaged Q-factor between the links with and without OPC versus conversion efficiency of the phase conjugator for 13 dBm of total power launched into the 480-km long optical link together with the corresponding averaged OSNRs.

#### 4. Conclusion

We have successfully demonstrated mitigation of nonlinear effects in a  $3 \times 32$ -Gbaud QPSK WDM transmission system over 480-km, 640-km and 800-km long links by using an optical phase conjugator placed in the middle of the link. For the first time, a silicon nanowire was used as nonlinear element for nonlinear compensation via phase conjugation. An improvement of 3.6 dB in Q-factor was achieved after 800-km transmission for 13 dBm of total power launched into each SSMF span, demonstrating that silicon waveguides can be effective as optical phase conjugators for Kerr nonlinearity distortion compensation. The influence of the OSNR degradation introduced by low conversion efficiency in the silicon waveguide was analyzed. It has been observed that this degradation clearly influences the performance of the system especially at lower input powers into the spans. Additionally, it has been shown that higher conversion efficiencies lead to higher improvement in Q-factor at high span input powers.

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